Food Research International 43 (2010) 1844–1855

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Climate change associated effects on grape and wine quality and production

Ramón Mira de Orduña *

Department of Food Science & Technology, NYSAES, Cornell University, Geneva, NY, USA

ARTICLE INFO

Article history:
Received 11 January 2010
Accepted 8 May 2010

Keywords:
Climate change
Vines
Grape
Wine
Vitis
Saccharomyces cerevisiae

ABSTRACT

Climate change is exerting an increasingly profound influence on vine phenology and grape composition, and ultimately affects vinifications, wine microbiology and chemistry, and sensory aspects. Among the most important climate change-related effects are advanced harvest times and temperatures, increased grape sugar concentrations that lead to high wine alcohol levels, lower acidities and modification of varietal aroma compounds. Under extremely hot temperatures, which are already being experienced in some regions, vine metabolism may be inhibited leading to reduced metabolite accumulations, which may affect wine aroma and color. Musts with high sugar concentrations cause a stress response in yeast, which leads to increased formation of fermentation co-products, such as acetic acid. If not controlled by acid addition, the higher pH can lead to significant changes in the microbial ecology of musts and wines and increase the risk of spoilage and organoleptic degradation.

1. Introduction

Over the last few years, occasional popular press articles have reported about the interest of winery owners from the well established Champagne region in purchasing land in more Northern regions, specifically England (Jones, 2004). While there is no indication for the migration of entire winemaking regions into more temperate climates because of climate change, it is undeniable that rising temperatures have already had a significant effect on the grape and wine industry. The tight correlation of vintage quality and annual weather conditions is well established. Not surprisingly, historical grape ripening data spanning back over 500 years has even been used as an indicator in climate research (Chuine et al., 2004). The potential effects of climate change on grape production have been discussed early on (Bindi, Fibbi, Gozzini, Orlandini, & Miglietta, 1996; Tate, 2001). This review provides a synopsis of the effect of climate change associated variables on grape composition, and critically analyzes their consequences on wine production and quality.

2. Effects on grape quality and production

2.1. Harvest dates and climate models

As expected for poikilothermic organisms, temperature is widely accepted to affect vine phenology, vegetative cycles and grape quality (Jackson & Lombard, 1993; Winkler, Cook, Kliewer, & Lider, 1974). Over the last years, observations from various world winemaking regions have provided evidence of modified vine development and fruit maturation pattern. Dates for budbreak, flowering and fruit maturity are now earlier in various regions.

A widespread observation is that harvest dates have advanced, especially in the last 10–30 years, even though archival information reaching back hundreds of years in some traditional winemaking areas confirm these trends over longer periods. Information from Johannisberg (Rheingau, Germany) shows that the first day of harvest now takes place an average of 2–3 weeks earlier than it was between the late 18th century and the early 20th century (Stock, Gerstengarbe, Kartschall, & Werner, 2005). Ganichot (2002) observed harvest dates that are 18 and 21 days earlier compared with the period from 1945 to 2000 for Chateauneuf du Pape and Tavel (southern France), respectively. In Alsace (eastern France), the mean annual temperatures increased 1.8 °C from 1972 to 2002 and this increase was especially significant during the ripening phase. In 2002, there were 33 more days with a mean daily temperature above 10 °C compared with 1972, and harvest was 2 weeks earlier (Duchêne & Schneider, 2005). In Baden (southwest Germany), the yearly average temperatures of the last 10 years were 1.2 °C higher than the average of 1961–1990 (Sigler, 2008). The average dates for the beginning of maturation (defined as equivalence of titratable acidity and density as expressed in °Oe) of Pinot Noir in Baden had advanced by 3 weeks from 1976 to 2006 (Sigler, 2008). In the Palatinate (Germany), annual average temperatures increased by 1.2 °C from 1970 to 2005 and harvest advanced 2 weeks (Petgen, 2007). In coastal California areas, average annual temperature increased by 1.13 °C and the start of the growing season advanced 18–24 days between 1951 and 1997 (Nemani et al., 2001).

* Tel.: +1 315 787 2266; fax: +1 315 787 2284.
E-mail address: rm369@cornell.edu

0963-9969/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodres.2010.05.001

Harvest dates need to be considered carefully since they are based on subjective evaluations of optimum fruit composition in view of ulterior wine quality, whose definition is exposed to individual interpretation and trends, and may also depend on commercial targets, market constraints, processing capacity and other factors. Over the last years there has been a clear inclination towards increased consideration of aroma or polyphenolic maturity in addition to the traditional measurement of technological variables, i.e. sugar and acid levels, leading to longer hang times. However, in spite of the trend toward longer hang times, harvest dates have advanced and fruit maturation occurs earlier. For example, measured on September 1st, grape potential alcohol levels increased by 2% (from 9.7 to 22.7 v/v%) across all grape cultivars in southern France between 1980 and 2001, while total acidity decreased from 6 to 4 g l^{-1} H_2SO_4 and the pH increased from 3 to 3.3 (Ganichot, 2002). Although the short time frame with available data needs to be interpreted with caution, maturity normalized for sugar advanced 0.5–3.1 days per year between 1993 and 2006 in Australia for three key cultivars, i.e. Cabernet Sauvignon, Chardonnay and Shiraz (Petrie & Sadras, 2008).

Several regional climate models have been presented in order to predict the overall effects of individual or combined climate change-related variables. Stock et al. (2005) presented a method for a regional climate model taking into account air temperature and other variables (e.g. precipitation, humidity, radiation, wind) and historical viticultural data. White, Diffenbaugh, Jones, Pal, and Giorgi (2006) modeled the suitability of regions in the USA for wine production based on temperature related viticultural data and concluded that by the end of the 21st century suitable winegrape production areas could decline by 81%. One third of the current Australian wine regions have been suggested to reach growing season temperatures unsuitable for quality wine production by 2070 (Hall & Jones, 2009). A combined temperature and phenological model suggested significantly earlier harvest dates (up to 45 days earlier than in 1990 for Coonawarra, Australia) for two grape cultivars in six Australian regions by 2050. Using a temperature based model, Lebon (2002) calculated grape ripening (veraison) to advance 3–5 weeks in southern France with a 2–4 °C increase in growing temperatures as compared with the baseline calculated from 1973–1992 averages.

2.2. Grape maturation

Approximately 10,000 grape cultivars are known in the Viticeae alone (Mullins, Bouquet, & Williams, 1992) providing significant biological diversity. While existing studies indicate a lack of uniformity in the degree of response to external factors across grape cultivars, a number of past and more current studies have examined common effects of climate change-related factors on vine phenology and grape ripening. During grape maturation, the concentration of sugars, amino acids, phenolic compounds and potassium increase, while the content in organic acids, particularly malic acid, decreases (Adams, 2006; Coombe, 1987; Ollat et al., 2002). For any given vineyard site, its soil, and to a certain degree the cultivar, remain constant. If viticultural variables remain constant, climate differences will have a major effect on fruit maturation and quality.

2.2.1. Effect of temperature

Warmer temperatures extend the period during which the minimal temperatures needed for the physiological activity of vines is reached, and hence, augment metabolic rates and affect metabolite accumulation (Coombe, 1987; Winkler et al., 1974). This is true within certain limits, since for temperatures above 25 °C, net photosynthesis decreases even at constant sun exposure (Huglin & Schneider, 1998). At such high temperatures, replacement of starch by lipids in leaf chloroplasts (Buttrose & Hale, 1971; Hawker, 1982) has been reported for grapevines, and above 30 °C, berry size and weight are reduced (Hale & Buttrose, 1974) and metabolic processes and sugar accumulation may completely stop (Coombe, 1987; Kriedemann & Smart, 1971).

Although high temperatures accelerate grape maturation, temperature effects on final sugar accumulation are reported to be relatively small (Coombe, 1987). Higher temperatures (30 °C) may lead to higher suspended solid concentrations, but Brix levels higher than 24–25 Brix are likely not due to photosynthesis and sugar transport from leaves and wood, but to concentration by evaporative loss (Keller, 2009, 2010). Hence, the extremely high sugar concentrations reached at harvest today, especially in warm climates, may be rather associated with the desire to optimize technical or polyphenolic and/or aromatic maturity. The effect of temperature on amino acids is thought to be minor. Except for proline, which is not degraded during winemaking (Ingledew, Magnus, & Sosulski, 1987), amino acids were not found to be affected by different temperatures (Buttrose, Hale, & Kliewer, 1971). A more considerable temperature effect is known for total acidity (Coombe, 1987; Tarara, Lee, Spayd, & Scagel, 2008). While the main grape acid, tartaric acid, is relatively stable with regards to temperature effects, malic acid levels are tightly dependent on maturity and temperature, and decrease with higher temperatures (Buttrose et al., 1971; Huglin & Schneider, 1998; Kliewer, 1971; Koblet et al., 1977; Ruffner, Hawker, & Hale, 1976). Lower acidity levels are usually also correlated with higher grape pH, though the relationship is affected by potassium accumulation, which is dependent on temperature itself. Specifically, during grape maturation, potassium levels increase significantly in grape clusters, which has been connected to redistribution from other above-ground vegetative vine organs (Hale, 1977; Williams & Biscay, 1991). Boulton (1980d) suggested that potassium enters berry cells in direct exchange for protons thus affecting berry and must pH for given total acidity (Boulton, 1980b, 1980c). The putative mediator for this exchange, a membrane-bound potassium/hydrogen ATPase in vegetative and reproductive tissues of grapevines (Boulton, 1980a), has been detected in grape seedling roots of various cultivars (Pinton, Varanini, & Maggioni, 1990). The effect of temperature on potassium accumulation in berries does not appear to be thoroughly studied, but several authors have suggested that higher temperatures lead to increased potassium levels (Coombe, 1987; Hale, 1981) and likely depend on viticultural variables such as rootstock (Huglin & Schneider, 1998) and cultivar (Pinton et al., 1990), as well. High temperature related increased potassium levels and lower total acidities have thus a combined effect on increased pH levels, that are now more frequently observed. Must pH values above 4 are readily reached in hot climates and have been recorded in traditional cool climates, too (Sigler, 2008).

Besides sugars, acids and potassium, higher temperatures also modify the accumulation of other compounds that are quantitatively less important but highly relevant for wine color and aroma. However, it should be noted that a specific temperature effect may be difficult to establish since solar radiation may exert a temperature effect, too. Sun exposure of grape clusters, which can be modified by viticultural practices, has been shown to lead to significantly higher berry temperatures (5–13 °C higher) compared with shaded grapes on the same vine (Huglin & Schneider, 1998; Kliewer & Lider, 1968; Lee et al., 2007; Ryona, Pan, Intrigliolo, Lakso, & Sacks, 2008; Spayd, Tarara, Mee, & Ferguson, 2002) but great efforts have been made to discriminate between these factors in some studies.

Flavonoids play a crucial role for grape and wine quality, with regards to color, aroma, bitterness and mouthfeel (Cohen, Tarara, & Kennedy, 2008; Downey, Dokoozlian, & Krstic, 2006). The fluctuation of phenolic compounds in grapes is significant, and its extent is cultivar dependent (Kliewer & Torres, 1972). Their role as photoprotectants explains their dependency on sun exposure (Caldwell, Bornman, Ballare, Flint, & Kulandaivelu, 2007). However, temperature has been shown to play a direct and important role in their formation, too (Huglin & Schneider, 1998). While low temperatures (14/9 °C day/night) are not conducive to large anthocyanin concentrations (Coombe, 1987), temperatures of 30 °C and higher also lead to lower anthocyanin synthesis (Buttrose et al., 1971; Spayd et al., 2002; Tarara et al., 2008), which may be completely and irreversibly inhibited at very elevated temperatures as Kliewer (1977) showed for Emperor at 37 °C day temperatures regardless of light exposure. It is suggested that in warm climates, grape berry temperature may frequently reach levels that inhibit formation of anthocyanins and hence reduce grape color (Downey et al., 2006). In a recent study, Cohen et al. (2008) showed that in Merlot grown in Prosser, WA, attenuating the diurnal temperature fluctuations led to increased ripening rates and higher anthocyanin concentrations at harvest. Besides absolute anthocyanin levels, compositional changes have also been described with warm seasons having been associated with increased formation of malvidin, petunidin, and delphinidin coumaroyl derivatives (Downey et al., 2006). However, Tarara et al. (2008) found high temperature associated decreases of delphinidin, cyanidin, petunidin and peonidin-based anthocyanins in sun-exposed Merlot berries, and reported malvidin derivatives to remain unaffected. The authors highlighted the complexity of combined solar radiation and temperature effects on flavonoid composition.

Grape skin and seed derived proanthocyanidins are important for red wine astringency. Several studies have shown a positive association between temperature and the number of seeds or total proanthocyanidin levels per berry at harvest (del Rio & Kennedy, 2006; Ewart & Kliewer, 1977). Similar effects have been reported in sun-exposed berries (Crippen & Morrison, 1986) reiterating the importance to discriminate between irradiation and temperature effects. It should also be considered that winemaking practices can largely alter the extraction of grape phenolics into wine (Kennedy, 2008; Zamora, 2003), but a review of these variables is beyond the scope of this work.

Practical experience suggests that white wine aromas develop more favorably in cool climates (Duchêne & Schneider, 2005). Examples of grape aroma compound classes relevant for white wine aroma of cultivars such as Gewürztraminer, Sauvignon Blanc or Riesling are isoprenoids and pyrazines. Sun exposure is necessary for accumulation of monoterpenes, which may impart fruity, floral or spicy aromas. Several studies suggested that, at equivalent sugar concentrations, higher temperatures led to lower levels in white aromatic grape varietals (Belancic et al., 1997; Reynolds & Wardle, 1993) thus potentially reducing aromatic intensity. On the contrary, warm temperatures have been correlated with increased formation of 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN), which may impart overly strong kerosene or petrol notes to Riesling, as well as other C13 norisoprenoids (Marais, 1993; Marais, Versini, Van Wyk, & Rapp, 1992). Methoxypyrazines (MPs) may be responsible for vegetal, herbaceous, or bell-pepper like aromas and are characteristic for some cultivars, such as Cabernet Sauvignon and Sauvignon Blanc, but may be perceived negatively at high concentrations. Anecdotal evidence and research obtained with red wine suggest that consumer preference tends towards wines with fruity notes rather than those with a prominent vegetal character (Fischer & Wilke, 2000; Lattey, Bramley, Francis, Herderich, & Pretorius, 2007). The sensory threshold of MPs are in the low parts per trillion range and their accumulation has been associated with cool viticultural conditions (Lacey, Allen, Harris, & Brown, 1991). High temperature and/or light exposure are positively correlated with lower MP levels (Allen & Lacey, 1993; Ryona et al., 2008). o-Aminoacetophenone (AAP) is an off-flavor that was first described in the 1990 in white wines that were considered to age prematurely, a phenomenon termed untypical or atypical ageing (Rapp, Versini, & Ullemeyer, 1993). The aroma of affected wines is generally described as acacia blossom, varnish or mothball like, and AAP is a degradation product of indole-3-acetic acid (Hoenicke, Borchert, Gruning, & Simat, 2002; Hoenicke, Simat, et al., 2002). While the exact formation mechanism and causatives remain poorly understood, it is presented here since its occurrence has been related to some variables, which may be climate change related, either in isolation, or in combination. In addition to nitrogen or mineral status, solar radiation, water stress, grape yield and harvest date were suggested as causatives (Hoenicke, Borchert, et al., 2002; Hoenicke, Simat, et al., 2002; Hühn, Sponholz, & Gafner, 1997; Schultz, 2000). However, results regarding some of the possible causatives were inconclusive (Linsenmeier & Loehnerz, 2007; Linsenmeier, Rauhut, Kurbel, Schubert, & Lohnertz, 2007) and masking effects seemed to play a role (Linsenmeier, Rauhut, Lohnertz, & Schubert, 2007). The appearance of this off-flavor appears to be less prevalent in other areas, such as Australia (Siebert, Herderich, Francis, & Pollnitz, 2003), and has been given little attention in the Northern American literature.

2.2.2. Effect of carbon dioxide

Atmospheric CO_2 concentrations have increased since industrialization and are predicted to rise further. Photosynthesis rates and growth are stimulated by CO_2 in nutrient sufficient plants (Long & Drake, 1992; Mullins et al., 1992; Schultz, 2000). Full plant exposure systems, so called Free Air CO_2 Enrichment (FACE) facilities that have been used for a variety of studies involving agricultural crops, trees and other plants (please see http://public.ornl.gov/face/global_face.shtml for overview) have been established to study the effect of enriched CO_2 concentrations on vine phenology and physiology under realistic field conditions (Bindi, Fibbi, Lanini, & Miglietta, 2001). Studies carried out by Bindi, Fibbi, Gozzini, Orlandini, and Seghi (1997) and Bindi, Fibbi, and Miglietta (2001) with 20 year-old Sangiovese grapevines in 1996 and 1997 found that atmospheric CO_2 levels elevated from current values of $\sim$370–550 µmol mol^{-1} increased biomass by 40–50% as total biomass and dry fruit weight. Acid and sugar levels were equally increased under elevated atmospheric CO_2 concentrations. However, at maturity no difference could be found among the treatments for these or other wine quality variables (Bindi et al., 2001). In the finished wines, there was a trend towards higher concentrations of red wine pigments in enriched treatments, which may have been related to vinification variables. It was concluded that the effect of higher CO_2 concentrations on grape and wine quality was limited and that yield increasing effects may be reduced or cancelled by the effect of warmer temperatures (Bindi et al., 2001). In order to account for these variables, Bindi et al. (1996) presented a mechanistic growth model, which was more sensitive to temperature and CO_2 than to radiation changes. A more recent study was presented by Goncalves et al. (2009) who studied Touriga Franca in field grown open top boxes with and without CO_2 fumigation. Overall, differences among grape maturity variables or wine aroma compounds were small or absent. However, most analyses were not carried out with grapes but wines fermented thereof, and may have suffered from fermentation factors. For example, differences were found between high and low CO_2 treatments for ethyl acetate ($p = 0.01$, $n = 3$) and diacetyl ($p = 0.063$, $n = 3$), which are fermentation co-products. Clearly, more studies involving *Vitis vinifera* in FACE systems will be required to clarify the possible effects of this variable.

2.2.3. Effect of radiation shifts

While radiation intensity may be controlled by varying vine and grape cluster exposure, this is not the case for the spectral quality.

The greenhouse gas associated reduction of stratospheric ozone levels has led to increases in UV-B radiation intensities, which may already have peaked, but are predicted to remain high for decades (McKenzie, Aucamp, Bais, Bjorn, & Ilyas, 2007). UV-B light mediated effects on ecosystems and crops may be variable (Caldwell et al., 2007; Krupa & Kickert, 1989). Viticulturally relevant consequences may stem from the effect of UV-B radiation on exposed fungal vine pathogens (Keller, Rogiers, & Schultz, 2003), which tend to be more susceptible to UV-B radiation than higher plants (Caldwell et al., 2007), as well as herbivorous insects and disease vectors (Caldwell et al., 2007), either directly, or mediated by an altered chemical composition of the vines. Caldwell et al. (2007) reviewed works that described the improvement of frost tolerance from UV-B in several plants. With regards to grape aroma, major effects may stem from changes in the composition of phenolic compounds (Lafontaine, Schultz, Lopes, Balo, & Varadi, 2005; Schultz et al., 1998), which play a significant role as photoprotective pigments in vines (Caldwell et al., 2007), and as antioxidants, color, aroma and mouthfeel relevant compounds in wines. Schultz (2000) reviewed some examples of possible UV-B radiation mediated consequences but the overall effects of increased UV-B radiation levels remain understudied.

2.2.4. Indirect effects of climate change

In addition to direct temperature effects on vine physiology and grape composition, there are important secondary effects, which are associated to changes in climate. Increased grape and wine salinity is a phenomenon associated with several semi-arid and arid regions relying on irrigation, such as parts of Australia and Argentina. Salinity derived attributes, such as "brackish", "seawater like", "soapy" are considered negatively and have been correlated with high wine concentrations of Na, K and Cl (Walker et al., 2003). Leske, Sas, Coulter, Stockley, and Lee (1997) reported average Cl levels of 3.97 mM in a survey of 1214 Australian red and white wines with maximum values reaching 52 mM. In comparison, Downton (1977) reported average Cl levels of 1.39 mM in French reds, 1.08 mM in Austrian and Italian reds and 0.58 mM in white wines from Germany, France and Portugal. In a study that measured chlorine in over 4000 wines across 3 years, Kaufmann (1996) found a significant correlation between high chlorine levels and arid producing regions. Average chlorine levels of 0.69 mM across all European red and white wines analyzed contrasted markedly with the 3.78 mM Cl average for wines produced in the USA, Mexico, Argentina and Australia. The uptake of ions was found to be cultivar (Cavagnaro, Ponce, Guzman, & Cirrincione, 2006) and rootstock dependent (Keller, 2009; Walker et al., 2003) and was also found to be affected by subsoil and irrigation water salinity, and irrigation methods (Leske et al., 1997; Smith, 2003).

Climate change has favored increased incidence of forest and bushfires (Overpeck, Rind, & Goldberg, 1990). In addition to the potentially significant loss of valuable ecological spaces, viticultural and enological consequences of wild bushfires, or prescribed burnings that go out of control were already felt in the Mediterranean, British Columbia, California and, especially, in Australia (Krstic, Logan, & Simos, 2008; Krstic, Martin, & Lowe, 2007; Turner, 2006) where smoke taints have been described in wines with the attributes dirty, burnt or ash (Howell, 2008, 2009; Simos, 2008; Vallesi & Howell, 2007). Studies on this taint and its remediation have been reported by the Australian Wine Research Institute since 2003 (Høj, Pretorius and Blair) and remain a high priority to date (Blair, 2009). A study by Kennison, Wilkinson, Williams, Smith, and Gibberd (2007) revealed guaiacol, 4-methylguaiacol, 4-ethylguaiacol, 4-ethylphenol, eugenol, and furfural in the headspace of wine made from grapes that had been exposed to straw derived smoke. Field experiments showed that smoke exposure had a cumulative effect (Kennison, Wilkinson, Pollnitz, Williams, & Gibberd, 2009) and guaiacol and 4-methylguaiacol were the most prevalent aroma compounds in Merlot made from smoke exposed grapes (Kennison, Gibberd, Pollnitz, & Wilkinson, 2008). While there were only traces present in the headspace of must, the headspace of finished wines contained large amounts (Kennison et al., 2008). The release of free guaiacol could also be achieved by enzymatic treatment or acid hydrolysis suggesting that in must, nonvolatile glycoconjugates prevailed (Kennison et al., 2008). Both compounds probably result from the combustion of lignin, are rapidly absorbed by developing berries (Sheppard, Dhesi, & Eggers, 2009) and have been identified in tainted wines at levels exceeding 10 times their sensory threshold (Høj, Pretorius, & Blair, 2003). However, it should be considered that wines may have a significant guaiacol background from toasted oak barrels (Pollnitz, Pardon, Sykes, & Sefton, 2004).

2.3. Effects on vine pests

Another climate change-related factor likely to influence grape production is the prominence of various pests and diseases, as well as the vectors responsible for disease distribution. An important disease which may move polewards is Pierce's disease caused by *Xylella fastidiosa*. The distribution of one of the most common vectors, the glassy winged sharpshooter, is highly temperature dependent and warmer winter temperatures may encourage the northern distribution of vector and/or pathogen (Daugherty, Bosco, & Almeida, 2009; Hoddle, 2004; Martensson, 2007). The same trend has been predicted for various pathogens introduced to Europe, including the causative of the fungal disease black rot, *Guignardia bidwellii*, or the flatid planthopper *Metcalfa pruinosa* (Maixner & Holz, 2003). Predictions diverge with regards to the leafhopper *Scaphoideus titanus*, the vector of the phytoplasma grapevine disease, flavescence dorée, and suggest that climate change may modify the complex interrelationships between vine and pest development (Stock et al., 2005) to the advantage of warmer viticultural regions. While Maixner and Holz (2003) predicted further range expansion of *S. titanus* to the north because of increasing temperatures, other research suggests that warmer temperatures do not necessarily involve higher pest pressure from *S. titanus*. For phytophagous univoltine pests, such *S. titanus*, synchronicity between larval and host organ development reduces larval starvation and mortality by providing insects with a maximum of nutrients immediately after hatching. Diapause termination and egg hatching of *S. titanus*, has been shown to necessitate cold winter temperatures (Chuche & Thiery, 2009). The lack of distribution of *S. titanus* in Southern Spain and Italy, as well as Greece (Chuche & Thiery, 2009), may be caused by delaying diapause break with regards to grape bud bursting, which occurs earlier at higher temperatures (Duchêne & Schneider, 2005). Accordingly, *S. titanus* may be negatively affected by further temperature increases. A viticulturally and enologically important organism is *Botrytis cinerea*, which may be involved in noble rot and often bunch rot. The former is a prerequisite for the production of highly priced sweet wines in specific regions, such as the Rheingau, Sauternes, Monbazillac, and Tokaji. A multitude of factors contribute to the formation of noble rot and temperature was found to be a factor for Tokaj wine quantity and quality, but future trends remain unclear (Makra et al., 2009). An Australian study (Steel & Greer, 2008) found that high inland temperatures (35–42 °C), while protecting from non-*Botrytis* bunch rots, lead to grape skin damage from sunburn, which was associated with latent *Botrytis* infections. Considering its importance for secondary infections and wine quality, the effect of climate change on bunch rots requires further studies.

2.4. Effect on root systems

Heat directed selectively on roots seems to have similar effects compared with above ground plant parts, and the timing of high temperatures as well as different day/night temperatures may modulate vine response (Coombe, 1987). Arbuscular mycorrhizal fungi were shown to be important for vine establishment and growth (Menge et al., 1983; Nogales et al., 2009), vine nutrient intake (Biricolti, Ferrini, Rinaldelli, Tamantini, & Vignozzi, 1997; Karagiannidis, Nikolaou, & Mattheou, 1995) and drought tolerance (Nikolaou, Angelopoulos, & Karagiannidis, 2003). Deleterious effects of UV-B radiation on mycorrhizal infection, possibly mediated by plant hormone levels, have been reported (van de Staaij, Rozema, van Beem, & Aerts, 2001), and more studies on the effect of climate change associated variables on rootstocks and root systems including mycorrhiza are warranted.

3. Winemaking consequences

Combined with longer hang times aimed at optimizing current perceptions of aromatic grape maturity, climate change has brought about a number of important winemaking challenges derived from grape composition. The main microbiological and technological challenges are higher temperatures of harvested grapes delivered to the winery, higher environmental temperatures during fermentations, higher grape berry sugar and, possibly, potassium concentrations, lower acidity levels and higher pH values.

3.1. Harvest conditions and fruit quality

During or after harvest and initial grape processing, grapes may be damaged favoring spoilage by indigenous microorganisms residing on berries and grape handling equipment, as well as chemical oxidation. These processes are promoted by increased temperatures and higher pH values which will be observed more frequently with the global rise in temperatures and advanced harvest dates. In Australia, temperatures in excess of 40 °C have been reported during harvest in hot years (Coulter, Henschke, Simos, & Pretorius, 2008).

Uncontrolled propagation of organisms can lead to a number of undesired consequences. A rapid onset of fermentation can reduce the effectiveness or even prevent cold settling, i.e. pre-fermentation sedimentation, through CO_2 formation induced mixing of musts. The competition of indigenous organisms for nutrients with yeast may lead to sluggish or stuck alcoholic fermentations (Bayrock & Ingledew, 2004). While this may be addressed with nutrient additions, the production of metabolites, such as acetic acid, may be problematic from an organoleptic point of view and can also interfere with yeast viability and fermentation efficiency (Edwards, Haag, & Collins, 1998; Edwards, Reynolds, Rodriguez, Semon, & Mills, 1999; Huang, Edwards, Peterson, & Haag, 1996; Rasmussen, Schultz, Snyder, Jones, & Smith, 1995). Other metabolites may be formed, such as acetaldehyde and pyruvate (Liu & Pilone, 2000), which combine with the preservative SO_2, or mycotoxins, which may pose a health or public relations problem. Mycotoxins are secondary metabolites produced by certain fungi and are of concern for human health, particularly as carcinogens (Leong et al., 2006). Overall, mycotoxin contamination of wines does not appear to be of major concern considering current legal limits and concentrations (Blesa, Soriano, Molto, & Manes, 2006; Leong et al., 2006; Soleas, Yan, & Goldberg, 2001). However, published research shows that its occurrence is a phenomenon correlated with warm winemaking regions and hence likely to expand with the increase in global temperatures. Specifically, a recent review by Blesa et al. (2006) indicated a correlation between climate and grape and wine ochratoxin A (OTA) levels. A survey of 942 wines by a regulatory laboratory showed that OTA concentrations were higher in wines from southern European than from northern European countries (Soleas et al., 2001).

Higher temperatures are also likely to exacerbate oxidative reactions in pre-fermentation stages (destemming, crushing, pressing, settling). For example, the concentration of several precursors of aroma compounds containing thiol groups that have been identified as key odorants in grape cultivars such as Sauvignon Blanc, Cabernet Sauvignon and Cabernet Franc, have been shown to decrease as a result of oxygenation (Blanchard, Darriet, & Dubourdieu, 2004; Maggu, Winz, Kilmartin, Trought, & Nicolau, 2007).

3.2. Effects of high sugar and alcohol concentrations

High sugar and the resulting ethanol concentrations can lead to a number of microbiological, technological, sensory and financial challenges. Increased sugar concentrations may cause growth inhibition or lysis in microorganisms. This is turn, may result in sluggish and stuck alcoholic fermentations, whose occurrence have been reported to increase drastically in hot years (Coulter et al., 2008), and which pose a significant problem to the wine industry. Reasons for stuck fermentations may be complex and include a number of factors (Bisson, 1999; D'Amato, Corbo, Del Nobile & Sinigaglia, 2006; Malherbe, Bauer, & du Toit, 2007; Santos et al., 2008) that are not reviewed here. However, in addition to causing fermentation performance issues, high but non-lethal sugar concentrations may produce osmotic stress in microorganisms, and affect wine quality. The hyperosmotic stress response of *Saccharomyces cerevisiae* in wine fermentations is strain dependent (Erasmus, Cliff, & van Vuuren, 2004; Ferreira, du Toit, & du Toit, 2006) and has been well studied in the context of very high sugar containing musts used in the production of botrytized wines (Bely, Masneuf-Pomarede, & Dubourdieu, 2005) or Icewines (Kontkanen, Inglis, Pickering, & Reynolds, 2004; Pigeau & Inglis, 2005b, 2007) that are fermented from musts with sugar levels of 32 to over 40 Brix. High sugar stress was found to up-regulate glycolytic and pentose phosphate pathway genes (Erasmus, van der Merwe, & van Vuuren, 2003) and leads to increased formation of fermentation by-products, including glycerol and acetic acid, which may exceed 1.5 g l^{-1} (Erasmus et al., 2004; Kontkanen et al., 2004; Nurgel, Pickering, & Inglis, 2004; Pigeau & Inglis, 2005a). These findings merit special attention since some outreach reports and anecdotal evidence suggest that spoiled grapes, acetic and lactic acid bacteria, and some non-*Saccharomyces* yeast, but not *S. cerevisiae*, continue to be widely regarded as the only significant sources of acetic acid. Instead, high levels of acetic acid exclusively derived from *S. cerevisiae* metabolism as evidenced by monoseptic fermentations of previously sterile filtered musts (Ferreira et al., 2006; Kontkanen et al., 2004) clearly show that concentrations may be reached in the production of table wines that near or exceed legal limits (about 1 g l^{-1} in most legislations).

Malolactic fermentation (MLF), a secondary fermentation carried out by wine lactic acid bacteria in most red and some white wines (Henick-Kling, 1993; Liu, 2002), may equally be affected by increasing and climate related high alcohol levels. Sluggish and stuck malolactic fermentations pose a threat to winemaking efficiency and wine quality by delaying ageing and stabilization operations and increasing the risk of sensory deviations (Lonvaud-Funel, 1999). Traditionally, MLF is induced in wines after the end of AF, where it may take place spontaneously by the organisms naturally present (Costello, Morrison, Lee, & Fleet, 1983). Among the factors that limit malolactic fermentability are low pH values, nutrient deficiencies, high concentrations of SO_2 or other inhibitors, and high ethanol levels, the latter having been shown to affect membrane integrity (Graca da Silveira, Vitoria

San Romao, Loureiro-Dias, Rombouts, & Abee, 2002; Guzzo & Desroche, 2009; Ribéreau-Gayon, Dubourdieu, Donèche, & Lonvaud-Funel, 1998a). By decarboxylation of malic to lactic acid and the potential production of ammonia from amino acid metabolism (Liu, Pritchard, Hardman, & Pilone, 1996), successful malolactic fermentation leads to a pH increase, which may exacerbate already high pH values in wines from hot climates that have not been acid adjusted. In addition, formation of acetic acid from sugar and citric acid metabolism may add acetic acid to the quantities stemming from the grapes and alcoholic fermentation (Henick-Kling, 1993). Because of the combined effect of the various inhibiting factors, difficult MLF may not only affect hot climates in the future, but also cool climates where moderately increased alcohol levels may lead to inhibition in conjunction with high acidity.

Alcoholic fermentations are exothermic processes leading to energy conservation as heat, and hence require efficient cooling, especially in the case of aromatic white wines, which normally are vinified at lower temperatures (10–15 °C). A value of approximately 24 kcal per mol of sugar is generally accepted for heat release during alcoholic fermentation, but other factors affect the total heat transfer, such as evaporative heat loss, the tank volume and its surface to volume ratio, as well as the fermentation temperature chosen (in temperature controlled fermentations) and its relation to the exterior temperature (Colombie, Malherbe, & Sablayrolles, 2007). Goelzer, Charnomordic, Colombie, Fromion, and Sablayrolles (2009) recently presented a simulation software, which is based on a combined physiological (Colombie, Malherbe, & Sablayrolles, 2005; Malherbe, Fromion, Hilgert, & Sablayrolles, 2004) and thermal model (Colombie et al., 2007), and also considers empirical data from a significant number of fermentations (Bely, Sablayrolles, & Barre, 1990). The simulation of alcoholic fermentation (SOFA) program (Goelzer et al., 2009) was used here to simulate maximum and total cooling energy requirements for a number of fermentations where the climate change-related variables "must sugar concentration" and "exterior temperature" were modified. Using the set of variables listed in Table 1, the model suggested a linear increase of approximately 5% in total cooling energy requirements for every increase of 1 °C of exterior temperature or 10 g l^{-1} in must sugar concentration. Combined increases of exterior temperature and sugar concentrations had a correspondingly synergistic effect. The sugar concentrations used for this simulation (approximately 22–27 Brix) are within the normal range for grapes harvested from warm climates. While an exterior temperature of 20 °C may be high for cool climates, even 24 °C cannot be considered excessive for warm climates, especially with regards to the advanced harvest dates now encountered. Increased cooling requirements can be considered a result of climate change, as well as further contributing to it unless sustainable energy sources were to be used. If the observed compression of harvest dates for various grape cultivars after heat waves (Coulter et al., 2008) is more common in the future, winery-wide peak cooling requirements may also further increase, potentially requiring larger cooling equipment.

Jones (2007) reviewed reports about increased alcohol levels in wines from Alsace, Australia and Napa and suggested 50% of the increase being attributable to climate change. The increase in the number of wines with alcohol levels above 13%, 14% and even 15% by volume in the marketplace is notable, as well as complaints about "heady" or "hot" wines by wine critics. Sensory studies have provided more detailed information about the role of ethanol. In a study with 24 trained subjects, Martin and Pangborn (1970) found ethanol (4–24 vol.%) to enhance the sweetness of sucrose and to reduce acid and saltiness perception of citric acid solution and NaCl, respectively. However, ethanol also increased the perceived bitterness of a quinine solution. Similar results were reported for phenolics derived from bittersweet English ciders where ethanol increased bitterness but decreased astringency (Lea & Arnold, 1978). In a study where a previously dealcoholized white wine was adjusted to various ethanol levels (8–14 vol.%), there was a trend towards reduced sourness perception from wines with increased ethanol levels (Fischer & Noble, 1994). More importantly, a large and significant effect of ethanol on perceived bitterness could be detected where a 3% increase in alcohol was found to be equivalent to the addition of 1400 mg l^{-1} of catechin to the base wine containing 100 mg l^{-1} catechin.

The effect of ethanol within the wine range (10–14 v/v%) on volatile ester hydrolysis in model solutions is reportedly low (Ramey & Ough, 1980). Several groups have also studied the effect of ethanol on volatility of wine aroma compounds. Increased ethanol concentrations have been found to reduce the equilibrium head space concentrations of most of the common wine volatiles studied including higher alcohols, esters, monoterpenes and pyrazines (Robinson et al., 2009), confirming results obtained elsewhere (Grosch, 2001; leBerre, Atanasova, Langlois, Etievant, & Thomas-Danguin, 2007). Fischer (2010) also reported lower headspace concentrations of several esters, including ethyl octanoate, 4-ethylphenol and 2-phenylethanol at high ethanol concentrations, and this correlated with reduced sensory perception. However, some important aroma compounds including linalool and 3-mercaptohexan-1-ol were found to be more volatile at high alcohol concentrations and, accordingly, their sensory threshold decreased under these conditions (Fischer, 2010). Using dynamic headspace methods, which mimic practical wine tasting conditions more closely, ethanol significantly enhanced the release of several volatiles (Taylor et al., 2010; Tsachaki, Linforth, & Taylor, 2005, 2009; Tsachaki et al., 2008), suggesting that in addition to odorant partition, mass transfer in the bulk phase needs to be considered as an essential parameter to assess the effect of changing alcohol concentrations on volatility and perception thresholds of aroma compounds in wines.

The possible contribution of higher ethanol concentrations and ethanol derived caloric intake to overweight and/or obesity should

Table 1
Simulation of maximum and total cooling energy needs according to various start sugar concentrations, exterior or set fermentation temperatures using the SOFA program (Goelzer et al., 2009).

Sugar [g l^{-1}]	Exterior temperature [°C]	Fermentation temperature [°C]	Peak cooling requirement [kW]	Difference [%]	Total cooling requirement [kW h]	Difference [%]
200	20	15	3.16	0.0	392	0.00
220	20	15	3.17	+0.40	434	+10.77
240	20	15	3.18	+0.70	478	+21.85
200	22	15	3.29	+4.27	429	+9.51
200	24	15	3.43	+8.54	466	+18.96
220	22	15	3.30	+4.67	476	+21.52
240	24	15	3.45	+9.20	573	+46.08

Model based on a 10,000 l volume and constant exterior and fermentation temperatures as specified. All musts were set to contain 300 mg l^{-1} of yeast assimilable nitrogen. Percent difference based on comparison with the fermentation of a must containing 200 g l^{-1} of sugar at 15 °C and 20 °C exterior temperature.

be considered critically. The disadvantages of Atwater-based factors for the determination of caloric values of foods and beverages are known (Livesey, 2001). The actual net metabolizable energy of nutrients available may vary, e.g. according to food digestibility and fermentability (Zou, Moughan, Awati, & Livesey, 2007), texture (Oka et al., 2003) or cooking (Wrangham & Conklin-Brittain, 2003). In mice, it has been shown that replacement of water with a 20 vol.% hydroalcoholic solution did not lead to weight gain (Smith et al., 2008). Conflicting evidence in this matter has been reviewed by Mattes (2006) who cited research that suggested that elevated thermogenesis or non-exercise activity thermogenesis may be responsible for the "alcoholic beverage energy paradox", i.e. increased energy intake without weight gain observed in some experimental and epidemiological studies. On the other side, the effect of higher ethanol concentrations on rate and extent of its absorption is well known (Holford, 1987; Ramchandani, Bosron, & Li, 2001). Accordingly, a potential for increased direct or indirect harm to human health by increased alcohol containing wines exists if consumption quantities and pattern are not reviewed. Certainly, higher alcohol levels may directly and significantly reduce competitiveness in markets where taxes and/or duties are directly linked to the alcohol content. For example, the federal excise tax in the USA changes from $1.07 to $1.57 per gallon of wine (+47%) for wines exceeding 14% of alcohol by volume (Anonymous, 2008b), a concentration that is easily reached in wines from hot climates today. The same threshold also leads to partly threefold higher excise taxes in several US States, including Ohio, Minnesota and New Mexico (Anonymous, 2008c) and thresholds of 13–14 vol.% may lead to higher custom tariffs in Canada, the USA, the EU and New Zealand (Anonymous, 2008a).

3.3. Microbial and sensory effects of lower acidities and increased potassium and pH levels

Low pH values are a cornerstone of microbiological stability. Accordingly, the trend towards higher pH values, if not corrected, harbor the risk of increased microbial contamination. This risk may be especially predominant at early stages of fermentations before higher alcohol concentrations lead to increased microbial stability. While growth of aerobic acetic acid bacteria should be avoided by ensuring anaerobic conditions, uncontrolled growth of lactic acid bacteria or spoilage yeast, such as *Dekkera/Brettanomyces*, may directly lead to a number of organoleptic deviations (Fugelsang & Edwards, 2007; Lonvaud-Funel, 1999) and include formation of biogenic amines and volatile phenols (Arvik & Henick-Kling, 2002; Couto, Campos, Figueiredo, & Hogg, 2006; Renouf, Lonvaud-Funel, & Coulon, 2007).

Kudo, Vagnoli, and Bisson (1998) showed high potassium levels to be a direct factor in causing stuck fermentations in a synthetic grape juice, especially if pH levels were low and hence, the potassium to hydrogen ion ratio high. Since this inhibition could not be prevented by nitrogen supplementation, pH reduction by acid addition without concomitant potassium removal may contribute to stuck fermentations. Microbial stability in finished wines may also be challenging at higher pH values, especially if high alcohol concentrations that usually accompany this phenomenon are reduced unilaterally, or residual sugars remain in the wine in order to avoid high alcohol concentrations. Generally suggested levels of molecular SO_2 to achieve microbial stability in dry wines range between 0.6 and 0.8 mg l^{-1}(Boulton, Singleton, Bisson, & Kunkee, 1996; Ribéreau-Gayon et al., 1998a). In order to reach these levels at 15 °C in a wine with 15% alcohol per volume and pH 4.0, a concentration of 95–126 mg l^{-1} of free SO_2 would be required, and 150–200 mg l^{-1} for the same wine at pH 4.2 (A. Bertrand, personal communication), which, after addition of some bound SO_2, would exceed legal limits for dry table wines in various legislations. There is insufficient evidence to suggest that the increased efficiency of SO_2 forms at low pH values is caused by the exclusive microcidal activity of molecular SO_2. The Henderson–Hasselbalch equation may be a good approximation for the calculation of SO_2 mediated microbiological wine stability at lower wine pH values, but cannot contribute to the mechanistic understanding of the complex interactions that influence microbial growth or inhibition, or provide a reasonable assessment of SO_2 requirements at the pH values observed today. More research is needed to reconsider the efficiency of SO_2 at higher pH levels, especially with regards to decreasing legal limits in the European Union.

Fischer and Wilke (2000) and von Nida and Fischer (1999) highlighted the good correlation between wine titratable acidity values and perceived acidity, while this was less applicable for pH values. In another study, Fischer and Noble (1994) found increased pH values to contribute to higher bitterness within the lower range of wine pH values (2.9–3.2). A study with over 400 German white wines found that consumers preferred wines with a mild and harmonic acid structure to acidity driven variants (Fischer & Wilke, 2000) suggesting a positive effect of climate change-associated lower acidities in cooler climates.

3.4. Climate change associated effects on wine chemistry

Climate change-related increases of the temperature, pH and potassium levels, especially in conjunction with higher sugar/alcohol concentrations, have a direct influence on wine chemistry, as well. Increased temperatures accelerate chemical reactions and thus, can exert a multitude of effects during production, ageing, transport or storage of wine. The temperature dependent increase of oxygen uptake (Ribéreau-Gayon, Glories, Maujean, & Dubourdieu, 1998b; White & Ough, 1973), browning (Berg & Akiyoshi, 1956) and reduction of SO_2 concentrations has been shown (Ough, 1985). Increased pH values also favor oxidative reactions (Boulton et al., 1996) and may affect wine color, taste and aroma. High pH favors the formation of the colorless hemiketal anthocyanin form reducing wine color in young red wines (Ribéreau-Gayon et al., 1998b). Together with the reduced formation of anthocyanins under hot viticultural conditions, this may constitute a significant overall effect in hot climate wines. The pH also mediates the reactivity of wine phenolics with regard to reaction rates and products as recently reviewed by Monagas and Bartolomé (2009), Terrier, Poncet-Legrand, and Chenynier (2009) and Santos-Buelga and de Freitas (2009). Higher pH values will decrease the rate of reaction of acid catalyzed hydrolyses, which would lead to increased stability of fermentation esters in high pH wines (Ramey & Ough, 1980) but also a slower release of aroma compounds from glycosidically bound precursors (Baumes, 2009; Williams, Strauss, & Wilson, 1980). The pH value was also shown to affect the intramolecular rearrangement of terpenes (Williams, Strauss, & Wilson, 1981; Williams, Strauss, Wilson, & Massywestropp, 1982) giving rise to species with different sensory thresholds (Ribéreau-Gayon et al., 1998b). The net charge of proteins and their solubility depends on the isoelectric point and must or wine pH. Accordingly, the pH may play a role in protein haze formation, for the efficiency of bentonite used for its prevention (Waters & Colby, 2009), as well as the effectiveness of proteinaceous fining agents (Marchal & Jeandet, 2009). Certainly, the activity of must and wine related enzymes also responds to pH changes. While some oxidation relevant enzymes, such as laccase, are stable under wine conditions, the pH optima of grape glycosidases and ß-lyases are beyond must and wine pH ranges (Ugliano, 2009). It remains to be studied whether increasing must pH values may have a relevant effect on the release of aroma compounds mediated by these enzymes. The consequences of climate change on tartrate stability in wines may be twofold, namely by causing increased potassium and alcohol levels, both of which will lower solubility of potassium tartrate in wines (Boulton et al., 1996) possibly requiring additional stabilization efforts to prevent bottle precipitations, which are considered unsightly.

A contaminant whose concentration may show a climate changed related rise is ethyl carbamate, a naturally occurring carcinogen in fermented foods (Battaglia, Conacher, & Page, 1990). Its formation by the reaction of ethanol and microbiologically produced precursors is favored by high temperatures and ethanol concentrations but lower at increased pH values (Ough, Crowell, & Gutlove, 1988). A major survey of 90,684 white and red table wines and 2516 fortified wines by a regulatory laboratory showed that across all table wines there was a downward trend from 1997 to 2001, while a slight increase was noticed from 2002 to 2006, which was especially pronounced for vintage wines (Soleas, 2007). While this trend is interesting and should be further observed, it should be noted that 87% of the wines tested between 1997 and 2006 had mean levels below 10 $\mu g\ l^{-1}$ and only 0.36% exceeded the maximum legal limit of 30 $\mu g\ l^{-1}$ established in Canada for table wines.

3.5. Effect on oak

Oak and, to a lesser degree, other suitable woods such as chestnut and cherry, have been traditionally used as container for wines. Today, its main role is to impart typical aromas to wines and a number of oak products (staves, chips, powders, etc.) may be used in addition to barrels. Tate (2001) reviewed the literature with regards to the potential effect of climate change on oak, and highlighted the possible effects of increased CO_2 concentrations on drought resistance, wood quality and ellagitannin concentrations, but also noted the overall scarcity of data available.

4. Summary

Climate change-associated shifts in grape quality will pose significant challenges for vinifications and final wine quality in the future, in particular concerning the expression of varietal grape aromas, microbiological and chemical stability and sensory balance. This review underlines the difficulties encountered in discriminating between the effects of various climate related variables (radiation, temperature, CO_2 concentration). In addition, climate change associated effects need to be separated from grape harvest and winemaking decisions, especially with regard to the greatly extended hang times that are now common in several winemaking regions and that may further aggravate climatic effects. The consequences of some variables are not well studied and may be rootstock and cultivar dependent. Predicting trends for surface evaporation, precipitations or winds has also proven difficult (Jones, 2007), and these have not been considered here. Research suggests that a majority of winemaking areas have operated under relatively ideal conditions (Jones, White, Cooper, & Storchmann, 2005) based on vintage quality ratings and year to year variation, especially cool climate winemaking regions (Jones & Davis, 2000). However, extreme conditions have already been experienced in hot winemaking regions where the future development is likely to have an overall negative impact on winegrape quality (Webb, Whetton, & Barlow, 2008). Several viticultural regions in Australia may become unsuitable for premium wine production in the current century (Hall & Jones, 2009) while several European regions may have to rethink current concepts of terroir with regards to cultivar selection and winemaking technology (Seguin & Garcia de Cortazar, 2005; White, Whalen, & Jones, 2009). Even in cooler climates that are said to have benefited from climate change so far (Jones & Davis, 2000), a more interventionist winemaking style involving water additions, acid adjustments and alcohol reductions, may be required in the future. The specific methods and technologies that are suitable and available to winemakers to address climate change-associated challenges will depend on the desired wine style and local regulatory circumstances.

Over the last years, traditional viticultural regions from the "old world" and those from the "new world" (mainly Canada, USA, Chile, Argentina, South Africa, Australia, New Zealand, China) have been joined by new regions that have been termed "new latitude" regions and comprise sites with tropical or meso-tropical climates in Peru, Thailand, Cambodia, India, Brazil and Venezuela now producing over 3 million tons of grapes annually (Possingham, 2008; Shaefer, 2008). Under these conditions, viticulture already faces considerable challenges, but little is known about the future difficulties.

A further area with significant need for work is the effect of climate change on wine consumption. A multitude of social and political factors exist that influence wine production, labeling, retail and advertisement. However, basic scientific knowledge is lacking on how climate change may affect human behavior. The increase in the consumption of cold, carbonated beverages, including beer, during warmer periods is well known (Lenten & Moosa, 1999). While there are some works that studied wine within the seasonality of alcohol consumption (Silm & Ahas, 2005), the possible effect of increasing external temperatures on the consumption of beverages with higher alcohol concentrations has not been considered.

Acknowledgement

The author wishes to acknowledge his gratitude to Dr. Gavin Sacks for critical and helpful comments.

References

Adams, D. O. (2006). Phenolics and ripening in grape berries. *American Journal of Enology and Viticulture, 57*, 249–256.

Allen, M. S., & Lacey, M. J. (1993). Methoxypyrazine grape flavour: Influence of climate, cultivar and viticulture. *Wein Wissenschaft, 48*, 211–213.

Anonymous (2008a). Comparison of wine tariffs (HTS codes 2204.29) for the EU, USA, Canada, and New Zealand. FIVS-Abridge database FIVS-Abridge LLC, Bethesda, MD, USA. <http://www.fivs-abridge.com> Accessed 20.01.10.

Anonymous (2008b). Imposition and rate of tax. *US Code TITLE* 26, section 5041(b).

Anonymous (2008c). State comparison of wine excise tax rates. Federation of tax administrators, p. 1.

Arvik, T., & Henick-Kling, T. (2002). *Brettanomyces bruxellensis* occurrence, growth, and effect on wine flavor. *Practical Winery and Vineyard*, 1–8.

Battaglia, R., Conacher, H. B. S., & Page, B. D. (1990). Ethyl carbamate (urethane) in alcoholic beverages and foods: A review. *Food Additives and Contaminants, 7*, 477–496.

Baumes, R. (2009). Wine aroma precursors. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 251–274). New York: Springer.

Bayrock, D. P., & Ingledew, W. M. (2004). Inhibition of yeast by lactic acid bacteria in continuous culture: Nutrient depletion and/or acid toxicity? *Journal of Industrial Microbiology & Biotechnology, 31*, 362–368.

Belancic, A., Agosin, E., Ibacache, A., Bordeu, E., Baumes, R., Razungles, A., et al. (1997). Influence of sun exposure on the aromatic composition of Chilean Muscat grape cultivars Moscatel de Alejandria and Moscatel rosada. *American Journal of Enology and Viticulture, 48*, 181–186.

Bely, M., Masneuf-Pomarede, I., & Dubourdieu, D. (2005). Influence of physiological state of inoculum on volatile acidity production by *Saccharomyces cerevisiae* during high sugar fermentation. *Journal International des Sciences de la Vigne et du Vin, 39*, 191–197.

Bely, M., Sablayrolles, J. M., & Barre, P. (1990). Description of alcoholic fermentation kinetics: Its variability and significance. *American Journal of Enology and Viticulture, 41*, 319–324.

Berg, H. W., & Akiyoshi, M. (1956). Some factors involved in browning of white wines. *American Journal of Enology and Viticulture, 7*, 1–7.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., & Miglietta, F. (1996). Modelling the impact of future climate scenarios on yield and yield variability of grapevine. *Climate Research, 7*, 213–224.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., & Seghi, L. (1997). The effect of elevated CO_2 concentration on grapevine growth under field conditions. In S. Poni, E. Peterlunger, F. Iacono, & C. Intrieri (Eds.). *Proceedings of the I international symposium on strategies to optimize wine grape quality* (Vol. 427, pp. 325–330). Conegliano, Italy: Acta Horticulturae.

Bindi, M., Fibbi, L., Lanini, M., & Miglietta, F. (2001). Free Air CO_2 Enrichment (FACE) of grapevine (*Vitis vinifera* L.): I. Development and testing of the system for CO2 enrichment. *European Journal of Agronomy, 14*, 135–143.
Bindi, M., Fibbi, L., & Miglietta, F. (2001). Free Air CO_2 Enrichment (FACE) of grapevine (*Vitis vinifera* L.): II. Growth and quality of grape and wine in response to elevated CO_2 concentrations. *European Journal of Agronomy, 14*, 145–155.
Biricolti, S., Ferrini, F., Rinaldelli, E., Tamantini, I., & Vignozzi, N. (1997). VAM fungi and soil lime content influence rootstock growth and nutrient content. *American Journal of Enology and Viticulture, 48*, 93–99.
Bisson, L. F. (1999). Stuck and sluggish fermentations. *American Journal of Enology and Viticulture, 50*, 107–119.
Blair, R (2009). *The Australian Wine Institute annual report*. AWRI: Adelaide, Australia.
Blanchard, L., Darriet, P., & Dubourdieu, D. (2004). Reactivity of 3-mercaptohexanol in red wine: Impact of oxygen, phenolic fractions, and sulfur dioxide. *American Journal of Enology and Viticulture, 55*, 115–120.
Blesa, J., Soriano, J. M., Molto, J. C., & Manes, J. (2006). Factors affecting the presence of ochratoxin A in wines. *Critical Reviews in Food Science and Nutrition, 46*, 473–478.
Boulton, R. (1980a). A hypothesis for the presence, activity, and role of potassium–hydrogen, adenosine triphosphatases in grapevines. *American Journal of Enology and Viticulture, 31*, 283–287.
Boulton, R. (1980b). Relationships between total acidity, titratable acidity and pH in wine. *American Journal of Enology and Viticulture, 31*, 76–80.
Boulton, R. (1980c). The general relationship between potassium, sodium and pH in grape juice and wine. *American Journal of Enology and Viticulture, 31*, 182–186.
Boulton, R. (1980d). The relationships between total acidity, titratable acidity and pH in grape tissue. *Vitis, 19*, 113–120.
Boulton, R. B., Singleton, V. L., Bisson, L. F., & Kunkee, R. E. (1996). *Principles and practices of winemaking*. New York: Chapman & Hall.
Buttrose, M. S., & Hale, C. R. (1971). Effects of temperature on accumulation of starch or lipid in chloroplasts of grapevine. *Planta, 101*, 166–170.
Buttrose, M. S., Hale, C. R., & Kliewer, W. M. (1971). Effect of temperature on composition of Cabernet Sauvignon berries. *American Journal of Enology and Viticulture, 22*, 71–75.
Caldwell, M. M., Bornman, J. F., Ballare, C. L., Flint, S. D., & Kulandaivelu, G. (2007). Terrestrial ecosystems, increased solar ultraviolet radiation, and interactions with other climate change factors. *Photochemical and Photobiological Science, 6*, 252–266.
Cavagnaro, J. B., Ponce, T., Guzman, J., & Cirrincione, M. A. (2006). Argentinean cultivars of *Vitis vinifera* grow better than European ones when cultured in vitro under salinity. *Biocell, 30*, 1–7.
Chuche, J., & Thiery, D. (2009). Cold winter temperatures condition the egg-hatching dynamics of a grape disease vector. *Naturwissenschaften, 96*, 827–834.
Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., & Ladurie, E. L. (2004). Historical phenology: Grape ripening as a past climate indicator. *Nature, 432*, 289–290.
Cohen, S. D., Tarara, J. M., & Kennedy, J. A. (2008). Assessing the impact of temperature on grape phenolic metabolism. *Analytica Chimica Acta, 621*, 57–67.
Colombie, S., Malherbe, S., & Sablayrolles, J. M. (2005). Modeling alcoholic fermentation in enological conditions: Feasibility and interest. *American Journal of Enology and Viticulture, 56*, 238–245.
Colombie, S., Malherbe, S., & Sablayrolles, J. M. (2007). Modeling of heat transfer in tanks during wine-making fermentation. *Food Control, 18*, 953–960.
Coombe, B. (1987). Influence of temperature on composition and quality of grapes. *Proceedings of the international symposium on grapevine canopy and vigor management* (Vol. XXII IHC, pp. 23–35). Davis, USA: ISHS Acta Horticulturae 206.
Costello, P. J., Morrison, G. J., Lee, T. H., & Fleet, G. H. (1983). Numbers and species of lactic acid bacteria in wines during vinification. *Food Technology in Australia, 35*, 14–18.
Coulter, A. D., Henschke, P. A., Simos, C. A., & Pretorius, I. S. (2008). When the heat is on, yeast fermentation runs out of puff. *Australian and New Zealand Wine Industry Journal, 23*, 26–30.
Couto, J. A., Campos, F. M., Figueiredo, A. R., & Hogg, T. A. (2006). Ability of lactic acid bacteria to produce volatile phenols. *American Journal of Enology and Viticulture, 57*, 166–171.
Crippen, D. D., Jr., & Morrison, J. C. (1986). The effects of sun exposure on the phenolic content of Cabernet Sauvignon berries during development. *American Journal of Enology and Viticulture, 37*, 243–247.
D'Amato, D., Corbo, M. R., Del Nobile, M. A., & Sinigaglia, M. (2006). Effects of temperature, ammonium and glucose concentrations on yeast growth in a model wine system. *International Journal of Food Science and Technology, 41*, 1152–1157.
Daugherty, M. P., Bosco, D., & Almeida, R. P. P. (2009). Temperature mediates vector transmission efficiency: Inoculum supply and plant infection dynamics. *Annals of Applied Biology, 155*, 361–369.
del Rio, J. L. P., & Kennedy, J. A. (2006). Development of proanthocyanidins in *Vitis vinifera* L. cv. Pinot noir grapes and extraction into wine. *American Journal of Enology and Viticulture, 57*, 125–132.
Downey, M. O., Dokoozlian, N. K., & Krstic, M. P. (2006). Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: A review of recent research. *American Journal of Enology and Viticulture, 57*, 257–268.
Downton, W. J. S. (1977). Salinity effects on ion composition of fruiting Cabernet Sauvignon vines. *American Journal of Enology and Viticulture, 28*, 210–214.
Duchêne, E., & Schneider, C. (2005). Grapevine and climatic changes: A glance at the situation in Alsace. *Agronomy for Sustainable Development, 25*, 93–99.
Edwards, C. G., Haag, K. M., & Collins, M. D. (1998). Identification and characterization of two lactic acid bacteria associated with sluggish/stuck fermentations. *American Journal of Enology and Viticulture, 49*, 445–448.
Edwards, C. G., Reynolds, A. G., Rodriguez, A. V., Semon, M. J., & Mills, J. M. (1999). Implication of acetic acid in the induction of slow/stuck grape juice fermentations and inhibition of yeast by *Lactobacillus* sp.. *American Journal of Enology and Viticulture, 50*, 204–210.
Erasmus, D. J., Cliff, M. A., & van Vuuren, H. J. J. (2004). Impact of yeast strain on the production of acetic acid, glycerol, and the sensory attributes of icewine. *American Journal of Enology and Viticulture, 55*, 371–378.
Erasmus, D. J., van der Merwe, G. K., & van Vuuren, H. J. (2003). Genome-wide expression analyses: Metabolic adaptation of *Saccharomyces cerevisiae* to high sugar stress. *FEMS Yeast Research, 3*, 375–399.
Ewart, A., & Kliewer, W. M. (1977). Effects of controlled day and night temperatures and nitrogen on fruit-set, ovule fertility, and fruit composition of several wine grape cultivars. *American Journal of Enology and Viticulture, 28*, 88–95.
Ferreira, J., du Toit, M., & du Toit, W. J. (2006). The effects of copper and high sugar concentrations on growth, fermentation efficiency and volatile acidity production of different commercial wine yeast strains. *Australian Journal of Grape and Wine Research, 12*, 50–56.
Fischer, U. (2010). Sensorische Bedeutung des Alkohols im Wein. Eine unterschätzte Einflussgröße. *Das Deutsche Weinmagazin, 5/6*, 108–110.
Fischer, U., & Noble, A. C. (1994). The effect of ethanol, catechin concentration, and pH on sourness and bitterness of wine. *American Journal of Enology and Viticulture, 45*, 6–10.
Fischer, U., & Wilke, A. (2000). Acidity structure and consumer preferences. Consumers do not enjoy acidity. *Deutsches Weinmagazin, 22*, 24–29.
Fugelsang, K. C., & Edwards, C. G. (2007). *Wine microbiology. Practical applications and procedures*. New York: Springer.
Ganichot, B. (2002). Evolution de la date des vendanges dans les Côtes du Rhône méridionales. In *6emes Recontres Rhodaniennes* (pp. 38–41). Orange, France: Institut Rhodanien.
Goelzer, A., Charnomordic, B., Colombie, S., Fromion, V., & Sablayrolles, J. M. (2009). Simulation and optimization software for alcoholic fermentation in winemaking conditions. *Food Control, 20*, 635–642.
Goncalves, B., Falco, V., Moutinho-Pereira, J., Bacelar, E., Peixoto, F., & Correia, C. (2009). Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): Volatile composition, phenolic content, and in vitro antioxidant activity of red wine. *Journal of Agricultural and Food Chemistry, 57*, 265–273.
Graca da Silveira, M., Vitoria San Romao, M., Loureiro-Dias, M. C., Rombouts, F. M., & Abee, T. (2002). Flow cytometric assessment of membrane integrity of ethanol-stressed *Oenococcus oeni* cells. *Applied and Environmental Microbiology, 68*, 6087–6093.
Grosch, W. (2001). Evaluation of the key odorants of foods by dilution experiments, aroma models and omission. *Chemical Senses, 26*, 533–545.
Guzzo, J., & Desroche, N. (2009). Physical and chemical stress factors in lactic acid bacteria. In H. König, G. Unden, & J. Fröhlich (Eds.), *Biology of microorganisms on grapes, in must and in wine* (pp. 293–306).
Hale, C. R. (1977). Relation between potassium and malate and tartrate contents of grape berries. *Vitis, 16*, 9–19.
Hale, C. R. (1981). Interaction between temperature and potassium and grape acids. In *CSIRO division of horticultural research report* (pp. 87–88). Glen Osmond, South Australia: CSIRO.
Hale, C. R., & Buttrose, M. S. (1974). Effect of temperature on ontogeny of berries of *Vitis vinifera* L. cv. Cabernet Sauvignon. *Journal of the American Society for Horticultural Science, 99*, 390–394.
Hall, A., & Jones, G. V. (2009). Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research, 15*, 97–119.
Hawker, J. S. (1982). Effect of temperature on lipid, starch and enzymes of starch metabolism in grape, tomato and broad bean-leaves. *Phytochemistry, 21*, 33–36.
Henick-Kling, T. (1993). Malolactic fermentation. In G. H. Fleet (Ed.), *Wine microbiology and biotechnology* (pp. 289–326). Chur, Switzerland: Harwood Academic Publishers.
Hoddle, M. S. (2004). llThe potential adventive geographic range of glassy-winged sharpshooter, *Homalodisca coagulata* and the grape pathogen *Xylella fastidiosa*: Implications for California and other grape growing regions of the world. *Crop Protection, 23*, 691–699.
Hoenicke, K., Borchert, O., Gruning, K., & Simat, T. J. (2002). "Untypical aging off-flavor" in wine: Synthesis of potential degradation compounds of indole-3-acetic acid and kynurenine and their evaluation as precursors of 2-aminoacetophenone. *Journal of Agricultural and Food Chemistry, 50*, 4303–4309.
Hoenicke, K., Simat, T. J., Steinhart, H., Christoph, N., Gessner, M., & Kohler, H. J. (2002). 'Untypical aging off-flavor' in wine: Formation of 2-aminoacetophenone and evaluation of its influencing factors. *Analytica Chimica Acta, 458*, 29–37.
Høj, P., Pretorius, I. S., & Blair, R. (2003). *The Australian Wine Institute annual report*. AWRI: Adelaide, Australia.
Holford, N. H. G. (1987). Clinical pharmacokinetics of ethanol. *Clinical Pharmacokinetics, 13*, 273–292.
Howell, G. (2008). Vintage 2008: The good, the bad and the heatwave. *Australian & New Zealand Grapegrower & Winemaker, 532*, 51–52.
Howell, G. (2009). Vintage 2009: Hazy days. *Australian & New Zealand Grapegrower & Winemaker, 544*, 47–48.

Huang, Y. C., Edwards, C. G., Peterson, J. C., & Haag, K. M. (1996). Relationship between sluggish fermentations and the antagonism of yeast by lactic acid bacteria. *American Journal of Enology and Viticulture, 47*, 1–10.

Huglin, P., & Schneider, C. (1998). *Biologie et écologie de la vigne*. Cachan, France: Éditions Tec & Doc Lavoisier.

Hühn, T., Sponholz, W. R., & Gafner, J. (1997). Causes of untypical aging flavour. *Schweizerische Zeitschrift für Obst- und Weinbau, Wädenswil, 133*, 636–638.

Ingledew, W. M., Magnus, C. A., & Sosulski, F. W. (1987). Influence of oxygen on proline utilization during the wine fermentation. *American Journal of Enology and Viticulture, 38*, 246–248.

Jackson, D. I., & Lombard, P. B. (1993). Environmental and management practices affecting grape composition and wine quality – A review. *American Journal of Enology and Viticulture, 44*, 409–430.

Jones, G. V. (2004). Making wine in a changing climate. *Geotimes, 49*, 24–28.

Jones, G. V. (2007). Climate change: Observations, projections, and general implications for viticulture and wine production. In *Whitman College Economics Department working paper* (pp. 1–7). Whitman College.

Jones, G. V., & Davis, R. E. (2000). Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture, 51*, 249–261.

Jones, G. V., White, M. A., Cooper, O. R., & Storchmann, K. (2005). Climate change and global wine quality. *Climatic Change, 73*, 319–343.

Karagiannidis, N., Nikolaou, N., & Mattheou, A. (1995). Influence of 3 Va-mycorrhiza species on the growth and nutrient-uptake of 3 grapevine rootstocks and one table grape cultivar. *Vitis, 34*, 85–89.

Kaufmann, A. (1996). Chloride in wine. *Deutsche Lebensmittel-Rundschau, 92*, 205–209.

Keller, M. (2009). Managing grapevines to optimise fruit development in a challenging environment: A climate change primer for viticulturists. *Australian Journal of Grape and Wine Research*, 1–14.

Keller, M., Rogiers, S. Y., & Schultz, H. R. (2003). Nitrogen and ultraviolet radiation modify grapevines' susceptibility to powdery mildew. *Vitis, 42*, 87–94.

Keller, M. (2010). *The science of grapevines: Anatomy and physiology*. New York: Academic Press.

Kennedy, J. A. (2008). Grape and wine phenolics: Observations and recent findings. *Ciencia e Investigacion Agraria, 35*, 107–120.

Kennison, K., Gibberd, M., Pollnitz, A., & Wilkinson, K. (2008). Smoke-derived taint in wine: The release of smoke-derived volatile phenols during fermentation of Merlot juice following grapevine exposure to smoke. *Journal of Agricultural and Food Chemistry, 56*, 7379–7383.

Kennison, K. R., Wilkinson, K. L., Pollnitz, A. P., Williams, H. G., & Gibberd, M. R. (2009). Effect of timing and duration of grapevine exposure to smoke on the composition and sensory properties of wine. *Australian Journal of Grape and Wine Research, 15*, 228–237.

Kennison, K. R., Wilkinson, K. L., Williams, H. G., Smith, J. H., & Gibberd, M. R. (2007). Smoke-derived taint in wine: Effect of postharvest smoke exposure of grapes on the chemical composition and sensory characteristics of wine. *Journal of Agricultural and Food Chemistry, 55*, 10897–10901.

Kliewer, W. M. (1971). Effect of day temperature and light intensity on concentration of malic and tartaric acids in *Vitis vinifera* L. grapes. *Journal of the American Society for Horticultural Science, 96*, 372.

Kliewer, W. M. (1977). Influence of temperature, solar-radiation and nitrogen on coloration and composition of Emperor grapes. *American Journal of Enology and Viticulture, 28*, 96–103.

Kliewer, W. M., & Lider, L. A. (1968). Influence of cluster exposure to sun on composition of Thompson seedless fruit. *American Journal of Enology and Viticulture, 19*, 175–184.

Kliewer, W. M., & Torres, R. E. (1972). Effect of controlled day and night temperatures on grape coloration. *American Journal of Enology and Viticulture, 23*, 71–77.

Koblet, W., Zanier, C., Tanner, H., Vautier, Ph., Simon, J.-L., & Gnägi, F. (1977). Reifeverlauf von Sonnen- und Schattentrauben. *Schweizerische Zeitschrift für Obst- und Weinbau, 113*, 558–567.

Kontkanen, D., Inglis, D. L., Pickering, G. J., & Reynolds, A. (2004). Effect of yeast inoculation rate, acclimatization, and nutrient addition on icewine fermentation. *American Journal of Enology and Viticulture, 55*, 363–370.

Kriedemann, P., & Smart, R. (1971). Effect of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. *Photosynthetica, 5*, 6–15.

Krstic, M., Logan, S., & Simos, C. (2008). Smoke taint study aims to understand more about the impacts on grape and wine industry. *Australian Viticulture*, 102–103.

Krstic, M., Martin, S., & Lowe, S. (2007). Influence of bushfires in north–east Victoria on smoke taint issues. *Australian Viticulture*, 31–33.

Krupa, S. V., & Kickert, R. N. (1989). The greenhouse effect: Impacts of ultraviolet-B (UV-B) radiation, carbon dioxide (CO_2), and ozone (O_3) on vegetation. *Environmental Pollution (Barking, Essex: 1987), 61*, 263–393.

Kudo, M., Vagnoli, P., & Bisson, L. F. (1998). Imbalance of pH and potassium concentration as a cause of stuck fermentations. *American Journal of Enology and Viticulture, 49*, 295–301.

Lacey, M. J., Allen, M. S., Harris, R. L. N., & Brown, W. V. (1991). Methoxypyrazines in Sauvignon Blanc grapes and wines. *American Journal of Enology and Viticulture, 42*, 103–108.

Lafontaine, M., Schultz, H., Lopes, C., Balo, B., & Varadi, G. (2005). Leaf and fruit responses of 'Riesling' grapevines to UV-radiation in the field. *Acta Horticulturae*, 125–131.

Lattey, K. A., Bramley, B. R., Francis, I. L., Herderich, M. J., & Pretorius, S. (2007). Wine quality and consumer preferences: Understanding consumer needs. *Australian and New Zealand Wine Industry Journal, 22*(1), 31–39.

leBerre, E., Atanasova, B., Langlois, D., Etievant, P., & Thomas-Danguin, T. (2007). Impact of ethanol on the perception of wine odorant mixtures. *Food Quality and Preference, 18*(6), 901–908.

Lea, A. G. H., & Arnold, G. M. (1978). Phenolics of ciders – Bitterness and astringency. *Journal of the Science of Food and Agriculture, 29*, 478–483.

Lebon, E. (2002). Changements climatiques: Quelles conséquences pour la viticulture. In *6emes Recontres Rhodaniennes* (pp. 31–36). Orange, France: Institut Rhodanien.

Lee, S. H., Seo, M. J., Riu, M., Cotta, J. P., Block, D. E., Dokoozlian, N. K., et al. (2007). Vine microclimate and norisoprenoid concentration in Cabernet Sauvignon grapes and wines. *American Journal of Enology and Viticulture, 58*, 291–301.

Lenten, L. J. A., & Moosa, I. A. (1999). Modelling the trend and seasonality in the consumption of alcoholic beverages in the United Kingdom. *Applied Economics, 31*, 795–804.

Leong, S. L., Hocking, A. D., Pitt, J. I., Kazi, B. A., Emmett, R. W., & Scott, E. S. (2006). Australian research on ochratoxigenic fungi and ochratoxin A. *International Journal of Food Microbiology, 111*, S10–S17.

Leske, P. A., Sas, A. N., Coulter, A. D., Stockley, C. S., & Lee, T. H. (1997). The composition of Australian grape juice: Chloride, sodium and sulfate ions. *Australian Journal of Grape and Wine Research, 3*, 26–30.

Linsenmeier, A., & Loehnerz, O. (2007). N fertilizers and atypical ageing off flavour. A lot does not help much. *Deutsche Weinmagazin, 7–8*, 64–66.

Linsenmeier, A., Rauhut, D., Kurbel, H., Schubert, S., & Lohnertz, O. (2007). Ambivalence of the influence of nitrogen supply on o-aminoacetophenone in 'Riesling' wine. *Vitis, 46*, 91–97.

Linsenmeier, A., Rauhut, D., Lohnertz, O., & Schubert, S. (2007). Untypical ageing off-flavour and masking effects due to long-term nitrogen fertilization. *Vitis, 46*, 33–38.

Liu, S.-Q. (2002). A review: Malolactic fermentation in wine – Beyond deacidification. *Journal of Applied Microbiology, 92*, 589–601.

Liu, S.-Q., & Pilone, G. J. (2000). An overwiew of formation and roles of acetaldehyde in winemaking with emphasis on microbiological implications. *International Journal of Food Science and Technology, 35*, 49–61.

Liu, S.-Q., Pritchard, G. G., Hardman, M. J., & Pilone, G. J. (1996). Arginine catabolism in wine lactic acid bacteria: Is it via the arginine deiminase pathway or the arginase–urease pathway? *Journal of Applied Bacteriology, 81*, 486–492.

Livesey, G. (2001). A perspective on food energy standards for nutrition labelling. *British Journal of Nutrition, 85*, 271–287.

Long, S. D., & Drake, B. G. (1992). Photosynthetic CO_2 assimilation and rising atmospheric CO_2 concentrations. In N. R. Baker & H. Thomas (Eds.), *Crop photosynthesis: Spatial and temporal determinants* (pp. 69–101). Amsterdam: Elsevier.

Lonvaud-Funel, A. (1999). Lactic acid bacteria in the quality improvement and depreciation of wine. *Antonie van Leeuwenhoek International Journal of General and Molecular Microbiology, 76*, 317–331.

Maggu, M., Winz, R., Kilmartin, P. A., Trought, M. C. T., & Nicolau, L. (2007). Effect of skin contact and pressure on the composition of Sauvignon Blanc must. *Journal of Agricultural and Food Chemistry, 55*, 10281–10288.

Maixner, M., & Holz, B. (2003). Risks by invasive species for viticulture. *Schriftenreihe des Bundesministeriums fur Verbraucherschutz, Ernahrung und Landwirtschaft, Reihe A, Angewandte Wissenschaft*, 154–164.

Makra, L., Vitanyi, B., Gal, A., Mika, J., Matyasovszky, I., & Hirsch, T. (2009). Wine quantity and quality variations in relation to climatic factors in the Tokaj (Hungary) winegrowing region. *American Journal of Enology and Viticulture, 60*, 312–321.

Malherbe, S., Bauer, F. F., & du Toit, M. (2007). Understanding problem fermentations – A review. *South African Journal of Enology and Viticulture, 28*, 169–186.

Malherbe, S., Fromion, V., Hilgert, N., & Sablayrolles, J. M. (2004). Modeling the effects of assimilable nitrogen and temperature on fermentation kinetics in enological conditions. *Biotechnology and Bioengineering, 86*, 261–272.

Marais, J. (1993). Factors affecting the development of 1,1,6-trimethyl-1,2-dihydronaphatalene in Riesling grapes and wine. In C. Bayonave, J. Crouzet, C. Flanzy, J. C. Martin, & J. C. Sapis (Eds.), *Actes du symposium international Connaissance aromatique des cépages et qualité des vins* (pp. 33–39). Lattes, France: Revue Française d'Oenologie.

Marais, J., Versini, G., Van Wyk, C., & Rapp, A. (1992). Effect of region on free and bound monoterpene and C-13-norisoprenoid concentrations in Weisser Riesling wines. *South African Journal for Enology and Viticulture, 13*, 71–77.

Marchal, R., & Jeandet, P. (2009). Use of enological additives for colloid and tartrate salt stabilization in white wines and for improvement of sparkling wine foaming properties. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 127–158). New York: Springer.

Martensson, A. (2007). Need for protective measures to combat potential outbreaks of *Homalodisca coagulata* and Pierce's disease in European viticulture. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science, 57*, 1–9.

Martin, S., & Pangborn, R. M. (1970). Taste interaction of ethyl alcohol with sweet, salty, sour and bitter compounds. *Journal of the Science of Food and Agriculture, 21*, 653–655.

Mattes, R. (2006). Fluid calories and energy balance: The good, the bad, and the uncertain. *Physiology & Behavior, 89*, 66–70.

McKenzie, R. L., Aucamp, P. J., Bais, A. F., Bjorn, L. O., & Ilyas, M. (2007). Changes in biologically-active ultraviolet radiation reaching the Earth's surface. *Photochemical & Photobiological Sciences, 6*, 218–231.

Menge, J. A., Raski, D. J., Lider, L. A., Johnson, E. L. V., Jones, N. O., Kissler, J. J., et al. (1983). Interactions between mycorrhizal fungi, soil fumigation, and growth of grapes in California. *American Journal of Enology and Viticulture, 34*, 117–121.

Monagas, M., & Bartolomé, B. (2009). Anthocyanins and anthocyanin-derived compounds. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 439–462). New York: Springer.

Mullins, M. G., Bouquet, A., & Williams, L. E. (1992). *Biology of the grapevine*. Cambridge, UK: Cambridge University Press.

Nemani, R. R., White, M. A., Cayan, D. R., Jones, G. V., Running, S. W., Coughlan, J. C., et al. (2001). Asymmetric warming over coastal California and its impact on the premium wine industry. *Climate Research, 19*, 25–34.

Nikolaou, N., Angelopoulos, K., & Karagiannidis, N. (2003). Effects of drought stress on mycorrhizal and non-mycorrhizal cabernet sauvignon grapevine, grafted onto various rootstocks. *Experimental Agriculture, 39*, 241–252.

Nogales, A., Luque, J., Estaun, V., Camprubi, A., Garcia-Figueres, F., & Calvet, C. (2009). Differential growth of mycorrhizal field-inoculated grapevine rootstocks in two replant soils. *American Journal of Enology and Viticulture, 60*, 484–489.

Nurgel, C., Pickering, G. J., & Inglis, D. L. (2004). Sensory and chemical characteristics of Canadian ice wines. *Journal of the Science of Food and Agriculture, 84*, 1675–1684.

Oka, K., Sakuarae, A., Fujise, T., Yoshimatsu, H., Sakata, T., & Nakata, M. (2003). Food texture differences affect energy metabolism in rats. *Journal of Dental Research, 82*, 491–494.

Ollat, N., Diakou-Verdin, P., Carde, J. P., Barrieu, F., Gaudillere, J. P., & Moing, A. (2002). Grape berry development: A review. *Journal International des Sciences de la Vigne et du Vin, 36*, 109–131.

Ough, C. S. (1985). Some effects of temperature and SO_2 on wine during simulated transport or storage. *American Journal of Enology and Viticulture, 36*, 18–22.

Ough, C. S., Crowell, E. A., & Gutlove, B. R. (1988). Carbamyl compound reactions with ethanol. *American Journal of Enology and Viticulture, 39*, 239–242.

Overpeck, J. T., Rind, D., & Goldberg, R. (1990). Climate-induced changes in forest disturbance and vegetation. *Nature, 343*, 51–53.

Petgen, M. (2007). Möglichkeiten und Grenzen der Reifesteuerung: Wie flexibel reagiert die Rebe? *Das Deutsche Weinmagazin, 7/8*, 42–47.

Petrie, P. R., & Sadras, V. O. (2008). Advancement of grapevine maturity in Australia between 1993 and 2006: Putative causes, magnitude of trends and viticultural consequences. *Australian Journal of Grape and Wine Research, 14*, 33–45.

Pigeau, G. M., & Inglis, D. L. (2005a). Upregulation of ALD3 and GPD1 in *Saccharomyces cerevisiae* during icewine fermentation. *Journal of Applied Microbiology, 99*, 112–125.

Pigeau, G. M., & Inglis, D. L. (2007). Response of wine yeast *Saccharomyces cerevisiae* aldehyde dehydrogenases to acetaldehyde stress during icewine fermentation. *Journal of Applied Microbiology, 103*, 1576–1586.

Pigeau, G., & Inglis, D. (2005b). Yeast metabolic implications of icewine fermentation. *American Journal of Enology and Viticulture, 56*, 418A.

Pinton, R., Varanini, Z., & Maggioni, A. (1990). Properties of potassium uptake by seedling roots of grape cultivars. *Plant and Soil, 123*, 175–179.

Pollnitz, A. P., Pardon, K. H., Sykes, M., & Sefton, M. A. (2004). The effects of sample preparation and gas chromatograph injection techniques on the accuracy of measuring guaiacol, 4-methylguaiacol and other volatile oak compounds in oak extracts by stable isotope dilution analyses. *Journal of Agricultural and Food Chemistry, 52*, 3244–3252.

Possingham, J. V. (2008). Developments in the production of table grapes, wine and raisins in tropical regions of the world. In P. G. Adsule, I. S. Sawant, & S. D. Shikhamany (Eds.). *Proceedings of the international symposium on grape production and processing* (Vol. 785, pp. 45–50). Baramati, Maharashtra, India: ISHS Acta Horticulturae.

Ramchandani, V. A., Bosron, W. F., & Li, T. K. (2001). Research advances in ethanol metabolism. *Pathologie Biologie, 49*, 676–682.

Ramey, D. D., & Ough, C. S. (1980). Volatile ester hydrolysis or formation during storage of model solutions and wines. *Journal of Agricultural and Food Chemistry, 28*, 928–934.

Rapp, A., Versini, G., & Ullemeyer, H. (1993). 2-Aminoacetophenone – Causal component of untypical aging flavor (naphthalene note, hybrid note) of wine. *Vitis, 32*, 61–62.

Rasmussen, J. E., Schultz, E., Snyder, R. E., Jones, R. S., & Smith, C. R. (1995). Acetic acid as a causative agent in producing stuck fermentations. *American Journal of Enology and Viticulture, 46*, 278–280.

Renouf, V., Lonvaud-Funel, A., & Coulon, J. (2007). The origin of *Brettanomyces bruxellensis* in wines: A review. *Journal International des Sciences de la Vigne et du Vin, 41*, 161–173.

Reynolds, A. G., & Wardle, D. A. (1993). Significance of viticultural and enological practices on monoterpene flavorants of British Columbia-grown *Vitis vinifera* berries and juices. *Wein Wissenschaft, 48*, 194–202.

Ribéreau-Gayon, P., Dubourdieu, D., Donèche, B., & Lonvaud-Funel, A. (1998a). *Traité d'Oenologie I*. Paris: Dunod.

Ribéreau-Gayon, P., Glories, Y., Maujean, A., & Dubourdieu, D. (1998b). *Traité d'Oenologie II*. Paris: Dunod.

Robinson, A. L., Ebeler, S. E., Heymann, H., Boss, P. K., Solomon, P. S., & Trengove, R. D. (2009). Interactions between wine volatile compounds and grape and wine matrix components influence aroma compound headspace partitioning. *Journal of Agricultural and Food Chemistry, 57*, 10313–10322.

Ruffner, H. P., Hawker, J. S., & Hale, C. R. (1976). Temperature and enzymic control of malate metabolism in berries of *Vitis vinifera*. *Phytochemistry, 15*, 1877–1880.

Ryona, I., Pan, B. S., Intrigliolo, D. S., Lakso, A. N., & Sacks, G. L. (2008). Effects of cluster light exposure on 3-isobutyl-2-methoxypyrazine accumulation and degradation patterns in red wine grapes (*Vitis vinifera* L. cv. Cabernet Franc). *Journal of Agricultural and Food Chemistry, 56*, 10838–10846.

Santos, J., Sousa, M. J., Carcloso, H., Inacio, J., Silva, S., Spencer-Martins, I., et al. (2008). Ethanol tolerance of sugar transport, and the rectification of stuck wine fermentations. *Microbiology – SGM, 154*, 422–430.

Santos-Buelga, C., & de Freitas, V. (2009). Influence of phenolics on wine organoleptic properties. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 529–570). New York: Springer.

Schultz, H. (2000). Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Australian Journal of Grape and Wine Research, 6*, 2–12.

Schultz, H. R., Lohnertz, O., Bettner, W., Balo, B., Linsenmeier, A., Jahnisch, A., et al. (1998). Is grape composition affected by current levels of UV-B radiation? *Vitis, 37*, 191–192.

Seguin, B., & Garcia de Cortazar, I. (2005). Climate warming: Consequences for viticulture and the notion of ´terroirś in Europe. In L. E. Williams (Ed.), *Proceedings of the VII international symposium on grapevine physiology and biotechnology* (pp. 61–69). Davis, USA.

Shaefer, W. W. (2008). Hot climate/tropical winemaking. In P. G. Adsule, I. S. Sawant, & S. D. Shikhamany (Eds.). *Proceedings of the international symposium on grape production and processing* (Vol. 785, pp. 477–482). Baramati, Maharashtra, India: ISHS Acta Horticulturae.

Sheppard, S. I., Dhesi, M. K., & Eggers, N. J. (2009). Effect of pre- and postveraison smoke exposure on guaiacol and 4-methylguaiacol concentration in mature grapes. *American Journal of Enology and Viticulture, 60*, 98–103.

Siebert, T., Herderich, M., Francis, L., & Pollnitz, A. (2003). No evidence of 'atypical ageing taint' in Australian white wine. *Australian & New Zealand Wine Industry Journal, 18*, 18.

Sigler, J. (2008). In den Zeiten des Klimawandels: Von der Süßreserve zur Sauerreserve? *Der Badische Winzer, 33*, 21–25.

Silm, S., & Ahas, R. (2005). Seasonality of alcohol-related phenomena in Estonia. *International Journal of Biometeorology, 49*, 215–223.

Simos, C. (2008). The implications of smoke taint and management practices. *Australian Viticulture*, 77–80.

Smith, F. (2003). Don't let the salt get into the wine. *Australian & New Zealand Grapegrower & Winemaker, 469*, 15–16.

Smith, R. R., Hong, J., Harvey, A. E., Lewis, T., Diaz, D., & Nunez, N. P. (2008). Ethanol consumption does not promote weight gain in female mice. *Annals of Nutrition and Metabolism, 53*, 252–259.

Soleas, G. J. (2007). A global survey of levels of undesirable metabolites in wine. In J. Aguado, E. M. Albert, S. Mínguez, C. de la Torre, B. Guamis, & O. Vilafranca del Penedés Guevara (Eds.), *Microsafetywine: International symposium on microbiology and food safety of wine*. Spain: INCAVI.

Soleas, G. J., Yan, J., & Goldberg, D. M. (2001). Assay of ochratoxin A in wine and beer by high-pressure liquid chromatography photodiode array and gas chromatography mass selective detection. *Journal of Agricultural and Food Chemistry, 49*, 2733–2740.

Spayd, S. E., Tarara, J. M., Mee, D. L., & Ferguson, J. C. (2002). Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. *American Journal of Enology and Viticulture, 53*, 171–182.

Steel, C., & Greer, D. (2008). Effect of climate on vine and bunch characteristics: Bunch rot disease susceptibility. *Proceedings of the international symposium on grape production and processing* (Vol. 785, pp. 253–262). Baramati, Maharashtra, India: Acta Horticulturae.

Stock, M., Gerstengarbe, F., Kartschall, T., & Werner, P. (2005). Reliability of climate change impact assessments for viticulture. In L. E. Williams (Ed.). *Proceedings of the VII international symposium on grapevine physiology and biotechnology* (Vol. 689, pp. 29–39). Davis, USA: Acta Horticulturae.

Tarara, J. M., Lee, J., Spayd, S. E., & Scagel, C. F. (2008). Berry temperature and solar radiation alter acylation, proportion, and concentration of anthocyanin in merlot grapes. *American Journal of Enology and Viticulture, 59*, 235–247.

Tate, A. B. (2001). Global warming's impact on wine. *Journal of Wine Research, 12*, 95–109.

Taylor, A. J., Tsachaki, M., Lopez, R., Morris, C., Ferreira, V., & Wolf, B. (2010). Odorant release from alcoholic beverages. In *Flavors in noncarbonated beverages* (pp. 161–175). Washington, DC: American Chemical Society.

Terrier, N., Poncet-Legrand, C., & Chenynier, V. (2009). Flavanols, flavonols and dihydroflavonols. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 463–507). New York: Springer.

Tsachaki, M., Gady, A. L., Kalopesas, M., Linforth, R. S. T., Athe|Çs, V., Marin, M., et al. (2008). Effect of ethanol, temperature, and gas flow rate on volatile release from aqueous solutions under dynamic headspace dilution conditions. *Journal of Agricultural and Food Chemistry, 56*, 5308–5315.

Tsachaki, M., Linforth, R. S. T., & Taylor, A. J. (2005). Dynamic headspace analysis of the release of volatile organic compounds from ethanolic systems by direct APCI-MS. *Journal of Agricultural and Food Chemistry, 53*, 8328–8333.

Tsachaki, M., Linforth, R. S. T., & Taylor, A. J. (2009). Aroma release from wines under dynamic conditions. *Journal of Agricultural and Food Chemistry, 57*, 6976–6981.

Turner, B. (2006). Smole-tainted grapes from burn-off threatens Margaret River growers. *Australian Viticulture*, 8.

Ugliano, M. (2009). Enzymes in winemaking. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 103–126). New York: Springer.

Vallesi, M., & Howell, G. (2007). The ashes we didn't want – Smoke taint in vintage 2007. *Australian & New Zealand Grapegrower & Winemaker, 520*, 66–67.

van de Staaij, J., Rozema, J., van Beem, A., & Aerts, R. (2001). Increased solar UV-B radiation may reduce infection by arbuscular mycorrhizal fungi (AMF) in dune grassland plants: Evidence from five years of field exposure. *Plant Ecology, 154*, 169–177.

von Nida, E., & Fischer, U. (1999). Säuremanagement II: Genuß ohne Reue [Acid management. II. Consumption without regret]. *Deutsche Weinmagazin, 10*, 28–33.

Walker, R. R., Blackmore, D. H., Clingeleffer, P. R., Godden, P., Francis, L., Valente, P., et al. (2003). Salinity effects on vines and wines. *Bulletin de l'O, IV*, 200–227.

Waters, E. J., & Colby, C. B. (2009). Proteins. In M. V. Moreno-Arribas & M. Carmen Polo (Eds.), *Wine chemistry and biochemistry* (pp. 213–230). New York: Springer.

Webb, L. B., Whetton, P. H., & Barlow, E. W. R. (2008). Climate change and winegrape quality in Australia. *Climate Research, 36*, 99–111.

White, B. B., & Ough, C. S. (1973). Oxygen uptake studies on grape juice. *American Journal of Enology and Viticulture, 24*, 148–152.

White, M. A., Diffenbaugh, N. S., Jones, G. V., Pal, J. S., & Giorgi, F. (2006). Extreme heat reduces and shifts United States premium wine production in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 11217–11222.

White, M. A., Whalen, P., & Jones, G. V. (2009). Land and wine. *Nature Geoscience, 2*, 82–84.

Williams, L. E., & Biscay, P. J. (1991). Partitioning of dry-weight, nitrogen, and potassium in Cabernet Sauvignon grapevines from anthesis until harvest. *American Journal of Enology and Viticulture, 42*, 113–117.

Williams, P. J., Strauss, C. R., & Wilson, B. (1980). Hydroxylated linalool derivatives as precursors of volatile monoterpenes of muscat grapes. *Journal of Agricultural and Food Chemistry, 28*, 766–771.

Williams, P. J., Strauss, C. R., & Wilson, B. (1981). Classification of the monoterpenoid composition of Muscat grapes. *American Journal of Enology and Viticulture, 32*, 230–235.

Williams, P. J., Strauss, C. R., Wilson, B., & Massywestropp, R. A. (1982). Use of C18 reversed-phase liquid-chromatography for the isolation of monoterpene glycosides and nor-isoprenoid precursors from grape juice and wines. *Journal of Chromatography, 235*, 471–480.

Winkler, A. J., Cook, J. A., Kliewer, W. M., & Lider, L. A. (1974). *General viticulture*. Berkely and Los Angeles: University of California Press.

Wrangham, R., & Conklin-Brittain, N. (2003). Cooking as a biological trait. *Comparative Biochemistry and Physiology A – Molecular & Integrative Physiology, 136*, 35–46.

Zamora, F. (2003). *Elaboración y Crianza del Vino Tinto: Aspectos Científicos y Prácticos*. Madrid, Spain: Ediciones Mundi Prensa.

Zou, M. L., Moughan, P. J., Awati, A., & Livesey, G. (2007). Accuracy of the Atwater factors and related food energy conversion factors with low-fat, high-fiber diets when energy intake is reduced spontaneously. *American Journal of Clinical Nutrition, 86*, 1649–1656.